Journal of South American Earth Sciences 103 (2020) 102723

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Analysis of groundwater and river stage fluctuations and their relationship with water use and climate variation effects on Alto Grande watershed, Northeastern Brazil

Eduardo A.G. Marques [a,*], Gerson C. Silva Junior [b], Glauco Z.S. Eger [b], Archange M. Ilambwetsi [a], Pousa Raphael [c], Tarcila N. Generoso [c], Josiane Oliveira [c], Jales N. Júnior [d]

[a] Civil Engineering Department, Universidade Federal de Viçosa, Viçosa, MG, 36570-900, Brazil
[b] Geology Department, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, 21941-916, Brazil
[c] Agriculture Engineering Department, Universidade Federal de Viçosa, Viçosa, MG, 36570-900, Brazil
[d] Geology Department, Universidade Federal do Oeste da Bahia, Barreiras, BA, 47808-021, Brazil

ARTICLE INFO

Keywords:
Climate variations
Irrigation
Groundwater drawdown
Stream flow reduction

ABSTRACT

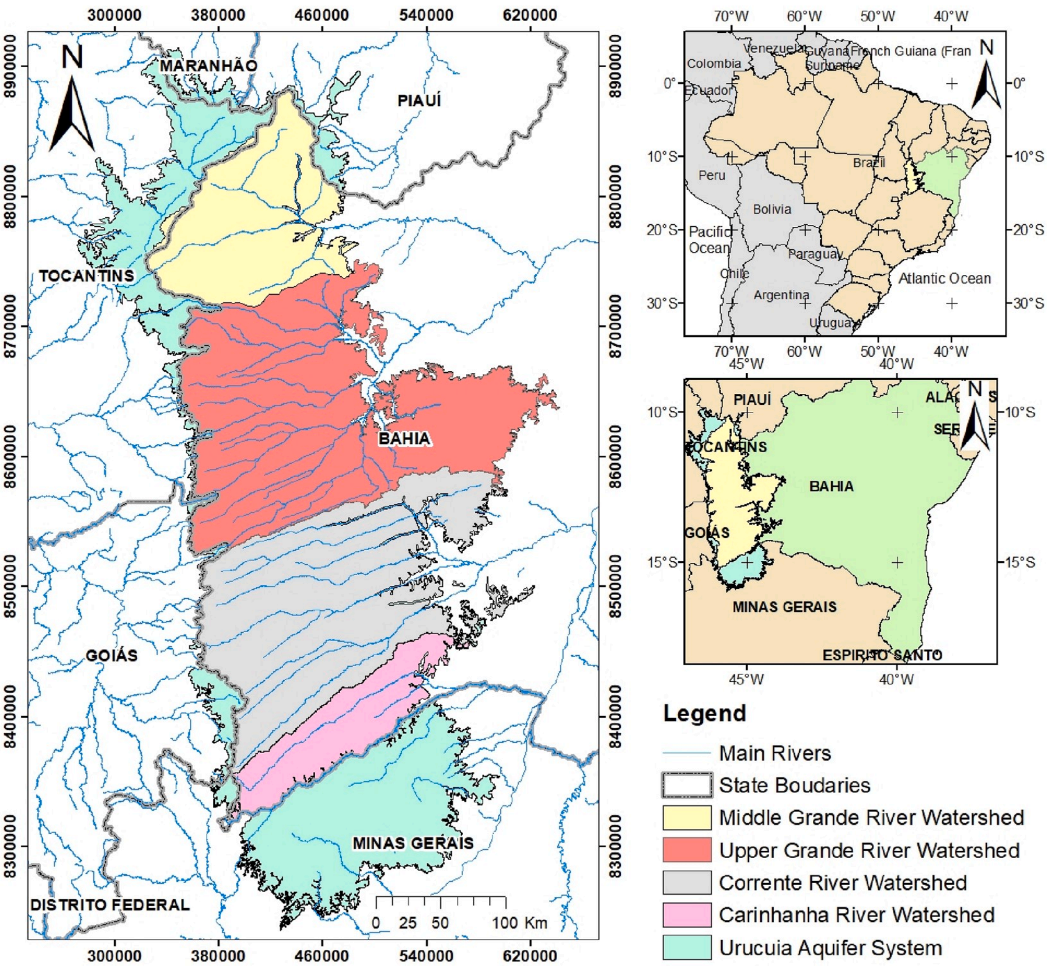
Sustainable use of water resources on the behavior of groundwater table and surface water level variations, especially in phreatic sedimentary aquifers, where a strong interaction between stream flow and groundwater normally takes place. In the present study, precipitation, water level fluctuation, river flow and pivot installation data from an important agricultural frontier with an increasing water use for irrigated agriculture and a downward precipitation trend were compared with surface and water level fluctuation monitoring data. The main purpose was to assess possible impacts on the aquifers and to analyze the variation in groundwater table and surface water levels due to long-term downward precipitation trend (climate variation effects) and increasing water demand (irrigation). A growing number of central pivots installed for irrigation are withdrawing water from the Urucuia Aquifer System (UAS) in western Bahia State, Northeastern Brazil, one of the leading agricultural frontiers of the world. Field surveys provided hydrogeological aspects that led to the construction of a hydrogeological conceptual model. Monitoring groundwater and surface water through Brazilian Geological Survey's Integrated Groundwater Monitoring Network (RIMAS-CPRM), satellite images and Hydrological Information System (HidroWeb-ANA) network formed the databases for the study. This data was compared with rainfall data and evolution of irrigated areas captured by satellite image analysis. Results indicate that reduction of rainfall volumes from 1990 to 2018 in the headwaters of Alto Grande basin, due to cyclic droughts, and an increase in surface and groundwater exploitation due to flourishing agribusiness activity has caused a considerable groundwater level drawdown. The drawdown of up to 6.63 m points to the need of strong management actions, which should provide a long-term sustainable use of water resources (superficial and underground) within Alto Grande watershed. This study is part of the actions undertaken to provide the scientific and technical basis to secure the availability of water and a sustainable agricultural activity, since an important part of the Cerrado, the Brazilian savanna ecosystem, and considerable proportion of São Francisco river flow, lies in the study area.

1. Introduction

Groundwater level and surface stream stage both depend on a number of factors, which determine their fluctuations through time. Generally, there is a connection between groundwater and surface water in a typical river basin, with the river channel either yielding (losing or influent river) or receiving (gaining or effluent river) water to or from the aquifer, respectively. There are also some cases where the aquifer is practically isolated from the overlaying surface water by an aquitard layer. Groundwater-surface water interaction varies widely depending on the watershed characteristics, such as rainfall volumes and regime, geology, land use, topography and vegetation. This interaction

* Corresponding author. Civil Engineering Department, Universidade Federal de Viçosa, Av. P. H. Rolfs S/No., Sala 115B, Edifício Sede do CCE, Campus Universitário, Viçosa, MG, 36570-125, Brazil.
E-mail address: emarques@ufv.br (E.A.G. Marques).

https://doi.org/10.1016/j.jsames.2020.102723
Received 8 May 2020; Received in revised form 15 June 2020; Accepted 24 June 2020
Available online 28 June 2020



(A)

Fig. 1. (A) Geology and location of the Urucuia Aquifer System (UAS) in Bahia, Brazil The dark green area also corresponds to the Urucuia plateau. (B) The four watersheds of UAS area in State of Bahia (Alto Grande watershed in light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

influences water quality and quantity as a whole in the catchment area (Kong et al., 2019). The main sources of streamflow are mostly rainfall and shallow groundwater, although deep groundwater plays an important role in the composition of the river yield in many areas (Vrzel et al., 2018; Frisbee et al., 2011). The contribution of each reservoir to the total discharge of the basin, their variability and geological conditionings are fundamental information to achieve an adequate management. They will also directly influence on the shape and oscillations of the stream hydrograph. Nevertheless, it is still a major scientific challenge to quantify properly each reservoir volume and temporal behavior.

Phreatic aquifers are a major water source for streamflow, and the groundwater contribution varies according to scale, generally increasing with the basin size, according to some recent studies. Storage capacity also determines how much groundwater flows to streams, and if younger or older water occurs (Rodríguez et al., 2018). However, research focusing on the geological and hydrogeological conditionings of stream flow generation in deep regional aquifers and their time variations is relatively scarce, with most studies dealing with small catchment areas (Shaw et al., 2014).

Management of agricultural areas, implementation and expansion of crop lands, irrigation systems, as well as seasonal, medium or long term climatic variations, all have a direct impact on aquifer recharge and, consequently, on the water availability in the system. Therefore, development of agricultural areas is subject to water accessibility, and recharge to aquifers determines the potential of the area and drives the management practices (Araujo et al., 2015). The water consumption also influences groundwater dynamics (Seabra et al., 2009; Bocanegra et al., 2016; Cristo et al., 2015; Kim et al., 2016; Manzione et al., 2016). Both surface water and groundwater are vital for agricultural irrigation and other rural uses, calling for an integrated management approach.

One common practice leading to resource mismanagement and scarcity is the use of one reservoir at the expense of the other, or allocating the same water twice, as well expressed by Kong et al. (2019). Unfortunately, it often occurs, with water permits sometimes exceeding the resource availability. Conflict for water rights arise, especially when a region lacks proper management measures and legal framework, with a variety of underlying causes, both socioeconomic and hydrologic.

Western portion of Bahia state, Brazil, has been undergoing a rapid agricultural expansion, beginning as recently as in the 1980–1990s. The region is located in the Cerrado biome, or Brazilian savanna. Irrigated agriculture is enduring an impressive expansion and projections point to further developments in the near future. Rio Grande basin is the most important and bigger watershed in Western Bahia, which includes two other main river basins, Corrente and Carinhanha, farther south. They are all part of the São Francisco River basin, the more important exclusively Brazilian river basin. Urucuia Aquifer System (UAS) is a great and mostly unconfined groundwater reservoir, formed on the homonymous geological group. It is fully connected to surface water

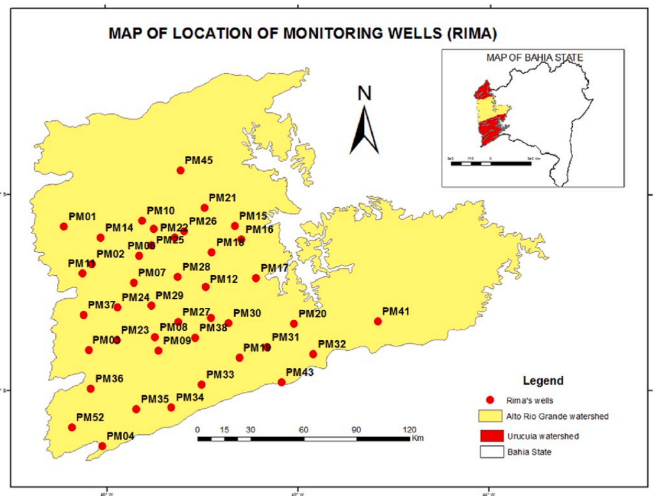


Fig. 2. Map with location of wells or RIMA's database used for the study.

streams and regulates their seasonal and interannual level variations (Pousa et al., 2019; ANA, 2013).

Implementation of an incipient groundwater monitoring network in Western Bahia in 2011, along with an older fluviometry and pluviometry control system, dating back to the early 20th century in a few measuring points, allows a much more precise control of water balance and availability in the region. Although the short history of the groundwater database offers some constraints to a proper interpretation, it is already possible to estimate the water system behavior, mass balance and assess the human impacts on the system. It also provides some initial understanding of the hydrological behavior within UAS region.

Therefore, the objective of this article is to evaluate the effects of an increasing groundwater and surface water pumping and observed climate multiannual variations over the hydrological system water balance in the Upper Rio Grande basin ("Alto Rio Grande"), located in Western Bahia (Fig. 1). We used groundwater level, precipitation and stream flow stage monitoring data to achieve the results. The objective is to present a panorama of the actual water volumes involved, indicate some environmental impacts observed, aiming to reduce or avoid water use conflicts in the future, by subsidizing appropriate measures and policies. This approach has successfully been used in some recent works in Urucuia Aquifer and elsewhere (Manzione et al., 2016; Wendland et al., 2007; Gonçalves et al., 2016; Gonçalves et al., 2020).

2. Study area

Urucuia Aquifer System comprises a total area of ca. 125.000 km^2, from the southern portion of Maranhão and Piauí States, through western State of Bahia, northeastern Goiás, southeastern Tocantins and northern Minas Gerais states. The main area of occurrence is in western Bahia State, forming the Urucuia Plateau, a vast elevated flat surface with a total area of 82.000 km^2 (Fig. 1). It gently tilts eastwards, with a series of parallel river basins draining surface and groundwater towards São Francisco River. The observed parallelism of the drainage channels is probably due to tectonic effects (Gaspar and Campos, 2007; Gaspar et al., 2012; Chang and Silva, 2015).

UAS represents a main natural asset in western Bahia and some adjacent portions of the surrounding states, with strategic importance, not only due to the growing water demand, but also for the vital role it plays on water flow regulation of São Francisco river basin (a source of heated debate between conservationists and the agribusiness entrepreneurs). It is also of great economic importance, as western Bahia State is a relatively new agriculture frontier, with a rapid land use change, increasing productivity gains and wealth creation in recent years. Groundwater resources in the region have an important function on the productivity and sustainability of local agribusiness, and their use are expected to grow further (Pimentel et al., 2000).

Natural river flow regime in the UAS is mostly perennial, with a strong contribution of groundwater in the composition of the total annual river outflow. Studies on the Urucuia Aquifer recharge to the rivers of the region indicate a high groundwater contribution rate to river streamflow. Pimentel et al. (2000), studying the Rio das Fêmeas basin, a tributary to Rio Grande, indicate that the mean annual outflow of this basin has a 90% groundwater contribution rate. The authors estimated a rainfall recharge of 250 mm/year to the UAS. An average recharge of 258.5 mm/year was calculated by Chang and Silva (2015),

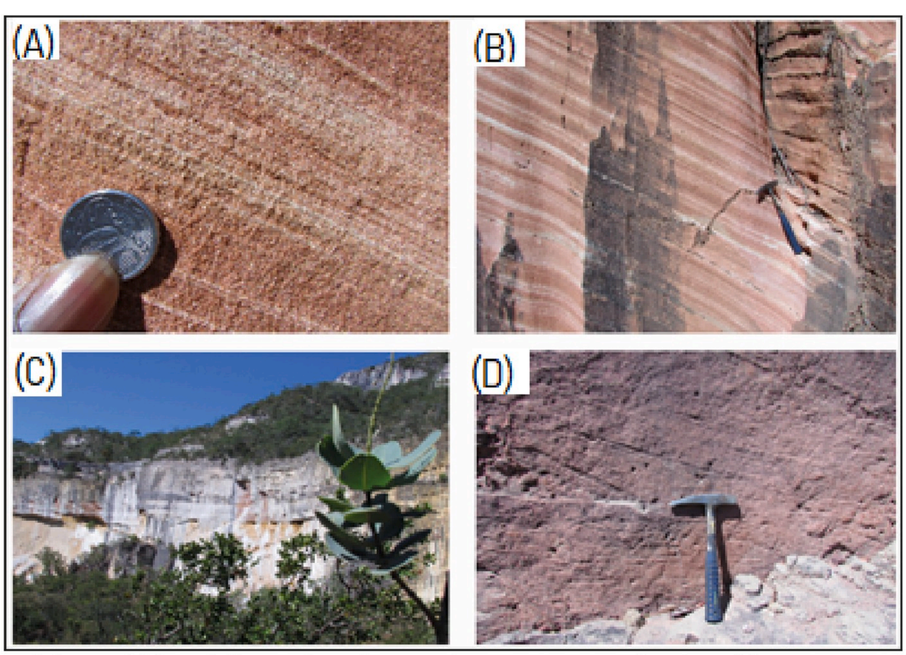


Fig. 3. (A, B) Rhythmicity and bimodalism of sandstones in Posse Formation is evident on a road cut in Tocantins State; (C) example of inclined bedding; (D) medium size dune structures.

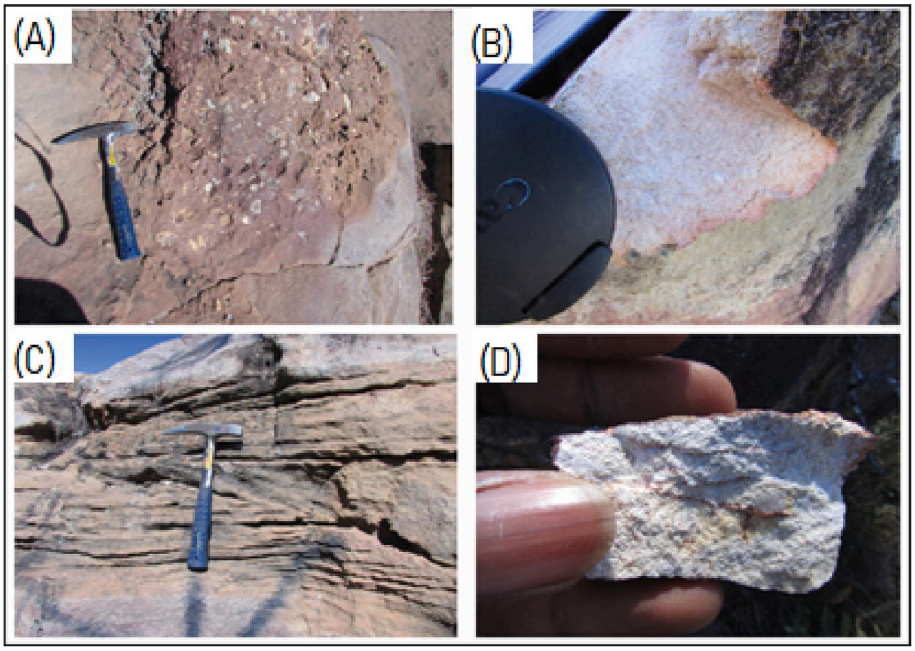


Fig. 4. (A) Iron conglomeratic rocks of Serra das Araras Formation; (B) Massive coarse sandstone with silicified contours at the contact with Posse Fm.; (C) Small size inclined bedding on medium sandstones near Barreiras city; (D) Quartz and politic lenses involved by an iron oxide film.

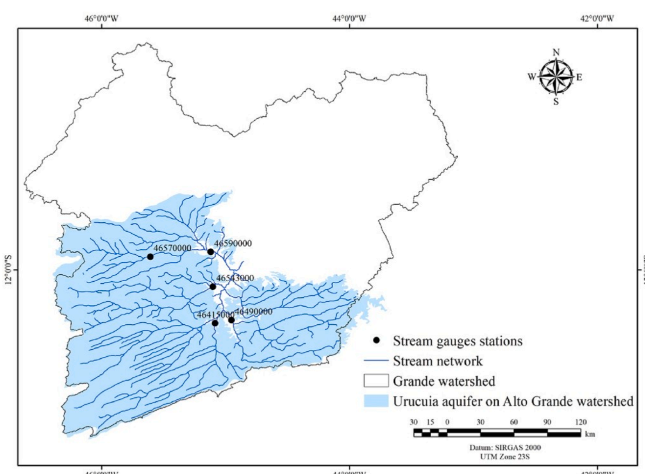


Fig. 5. Location of stream gauges used on the study.

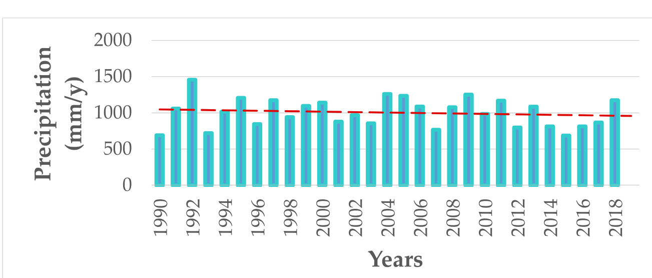


Fig. 6. Blue bars show the annual average rainfall from 1990 to 2019 for Alto Grande watershed area. Red dashed line is the linear regression of annual data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

corresponding to ca. 20% of the mean precipitation for the period between 1984 and 1995. In the present study, the average estimated recharge was about 17.3% of the total mean precipitation, with basis on a work carried by the Brazilian National Water Agency (ANA, 2017) and the author's fieldwork. Gonçalves et al. (2016) estimated UAS baseflow corresponding to 81.75%–93.06% of the Grande river discharge, varying seasonally. Those authors also claimed that the decreasing rate of baseflow from 1977 to 2013 is bigger than the rate of precipitation, pointing to a possible over-exploitation of the aquifer.

In western Bahia, within the UAS area, the Integrated Groundwater Monitoring Network (RIMAS) of the Brazilian Geological Survey (CPRM) comprises 61 monitoring wells, of which 42 are in the Rio Grande basin (Fig. 2), with automatic data logger devices taking groundwater head measurements each day. RIMAS network began operation in western Bahia only in the year 2011, right in the Alto Grande river basin.

The UAS comprises rocks from Cretaceous Urucuia Group, subdivided into two formations: Posse (lower unit) and Serra das Araras (upper unit) (Fig. 1). The Group consists predominantly of eolian sandstones, with some fluvial texturally heterogeneous deposits. The tectonic depression in which the sediment accumulated reflects the propagation of tensions originated with the opening and spreading of the Atlantic Ocean. Sandstones occur throughout the basin and are composed essentially of quartz grains, with some evidence of depositional sedimentary structures. Very fine, fine, medium and thick sandstone layers have peculiar characteristics that allow differentiating the two aforementioned units making up the Urucuia Group (Campos and Dardenne, 1999; Amorim Jú nior and Lima, 2007; Barbosa et al., 2017).

The main characteristics of Posse Formation are cross-stratifications from large dunes and a horizontal stratification in friable and fine to medium grain size sandstones, intercalated with clays and silts. The UAS plateau ends abruptly in the western border, forming the cliffs of Serra Geral de Goiás ridge. Fig. 3 presents some general aspects of the Posse Formation sandstones.

Serra das Araras Formation is the upper unit of the Urucuia Group and shows up in all basin areas. It consists of medium to thick sandstones with a bulky aspect, and small size inclined bedding Sometimes the sandstone recrystallizes, forming extensive silicified but thin layers with low permeability, especially near the contact with Posse Formation

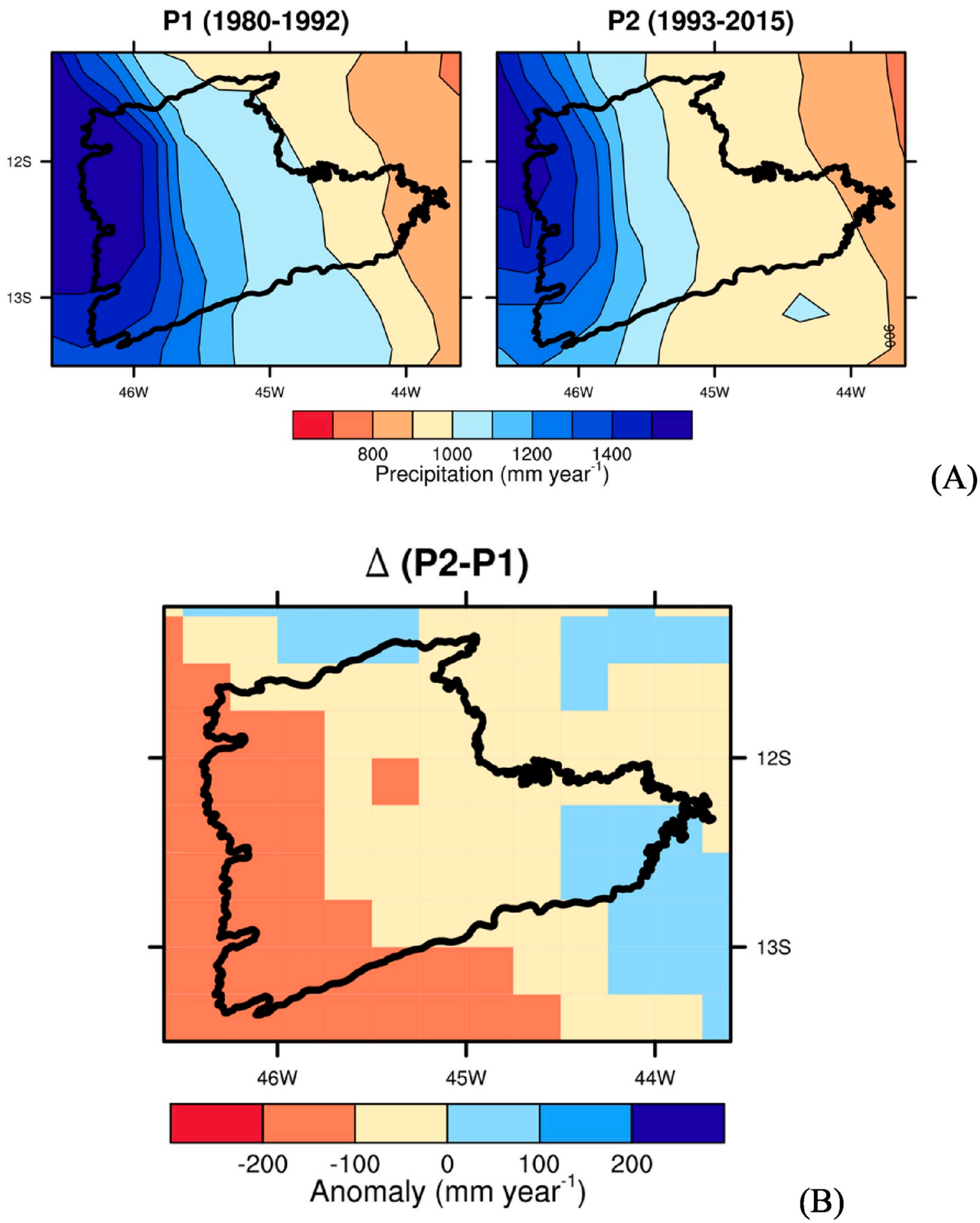


Fig. 7. (A) Average precipitation maps for periods P1 and P2 (variation from 1980 to 2015) for Alto Grande watershed. (B) Delta values of precipitation (difference between P1 and P2) observed between the two periods shown on Fig. 7A.

(Fig. 4). The tabular silicified levels appear in various stratigraphic positions (Bonfim and Gomes, 2004).

3. Materials, methods and data analysis

Fieldwork initiated with a geological reconnaissance, held to determine lithological, mineralogical, petrographic and structural aspects to support the geological conceptual modeling of the study area. Some basic aspects of UAS hydrogeology remain poorly known, as the location and extension of the confining or semiconfining unit at the base of Serra das Araras Formation and the real depth of the Posse Formation (the lower aquifer). Processing field and literature data enabled the construction of a hydrogeological conceptual model, with UAS limits and layer thickness, as well as boundary conditions definition and

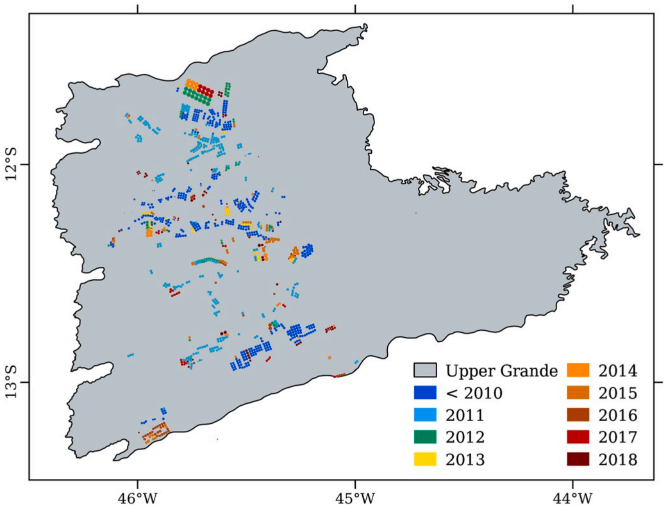


Fig. 8. Central pivots installed on Alto Grande watershed from 2010 to 2018.

confinement characteristics.

Aquifer potentiometry monitoring data from RIMAS network was a basic tool for the work. Monitoring is automatic, with one daily reading. In the present study, the total variation of the regional water table, obtained from RIMAS database monitoring data, resulted in a set of data showing head variations between the initial static groundwater level measured on the beginning of monitoring, and the subsequent water level measurements conditioned by natural (rainfall) or man-induced variations.

Streamflow series data used in the interpretation, obtained in five stream gauges, are part of the HIDROWEB hydrometeorological network, the web-based hydrological information system from Brazilian National Water Agency (ANA), shown in Fig. 5.

Filtering of the base period consisted in selecting data only from stations with a minimum 20 years continuous interval series, with at least 95% of the total annual expected data effectively existent in the dataset. Therefore, the period from 1977 to 2015 fitted these basic requirements for the selected gauge streams and thus was selected for the study.

Both the long-term average streamflow (Q_{lt}: long-term flow corresponding to the daily flow average for the period under study) and the minimum streamflow (Q_{90}: permanent streamflow, where ''permanent'' means ''present 90% of the time'') were evaluated. The permanence curve, which describes the frequency at which the streamflow is greater than, or equal to, the reference value in the y-coordinate was constructed (Pruski et al., 2013). For the five stream gauges of the present study a computational system for meteorological and hydrological studies – the *Hydrology Plus* was used (Sousa, 2017) to retrieve and treat data. Data from 1977 to 2010, and from 2011 to 2017 were analyzed.

Precipitation data from the database of rainfall stations in the area, for the period 1990–2018, underwent a cross-validation approach to arrive on data interpolated and distributed throughout the study area.

Finally, satellite images showed the progressive increase in the number of installed pivots from 1990 to 2018, and an analysis of the increase in water use followed suit. These data are visualized in the website <http://obahia.dea.ufv.br>, developed specifically for the present research, and currently under updating by the authors. The annual streamflow evolution analysis was compared with groundwater level monitoring data, for which information is available for the period 2011–2018. Although the timing of the three time series is not coincident, it was possible to integrate interpretation of the stream water and groundwater abstraction with the rainfall variation and ensuing impacts in available water resources.

4. Results and discussion

4.1. Precipitation variation

Mean annual rainfall rate on Alto Grande basin, São Desidério area (Fig. 6) presents a smooth declining linear trend throughout the 1990–2019 period, with the Mann-Kendall statistical test showing it with an error rate $\alpha = 0.25$. For the 2003–2018 period, though, the declining trend is more significant, with $\alpha = 0.05$.

This may be due to the effect of a local climate variation, as shown in Fig. 7, which shows the precipitation measured in the Alto Grande basin area over the last 35 years.

From Figs. 6 and 7, the highest precipitation area has evidently moved westwards, resulting in a reduction of the average precipitation of up to 200 mm per year in the Alto Grande basin area, a phenomenon not observed at the discharge area of the basin, eastwards. Fig. 7 is a detailed zoom to Alto Grande watershed, based on data collected by Xavier et al. (2016) and Pousa et al. (2019). In this work, the authors have made a statistical analysis (Mann-Kendall test) that indicates precipitation trends consist both in sign and in significance ($\alpha = 0.10$) with the precipitation differences (Fig. 7A).

4.2. Central pivot deployment

Fig. 8 shows the evolution of central pivots deployment for irrigation in Alto Grande River basin from 2011 (when there was already a considerable number of pivots in the basin) to 2018. Pivots were implanted mainly in the years before 2010 and during 2011, and with a constant rate since 2012. It also shows that increase in the number of pivots was concentrated in the central western portion of the Alto Grande basin, precisely in the segment with the biggest reduction in rainfall volumes for the monitored period. The irrigated area has increased from almost 74.000 ha on 2010 to almost 120.000 ha on 2018.

Associating the increase in water use demand (surface and subsurface waters) for irrigation with the discrete reduction of rainfall volume (lower supply), presented previously on item 4.1, an assessment of these two processes in the basin hydrological regime is possible. Evaluation of both groundwater and surface water availability, respectively through the well net monitoring and fluviometric gauge data, are discussed later on in the text.

Table 1
Variation of long-term average and minimum flow on selected river gauging stations.

Station Codes	Q_{lt} (m^3/s)		RP (%)	Q_{90} (m^3/s)		RP (%)
	(1977–2010)	(2011–2017)		(1977–2010)	(2011–2017)	
46415000	30,90	20,37	34,09	18,79	12,10	35,61
46490000	5,79	3,10	46,43	3045	1,42	53,53
46543000	48,08	33,41	30,51	33,06	21,43	35,17
46570000	14,08	9,13	35,14	7,10	3,32	53,30
46590000	49,87	37,97	23,85	35,74	27,11	24,14
Mean	29,74	20,80	34,00	19,55	13,08	40,35

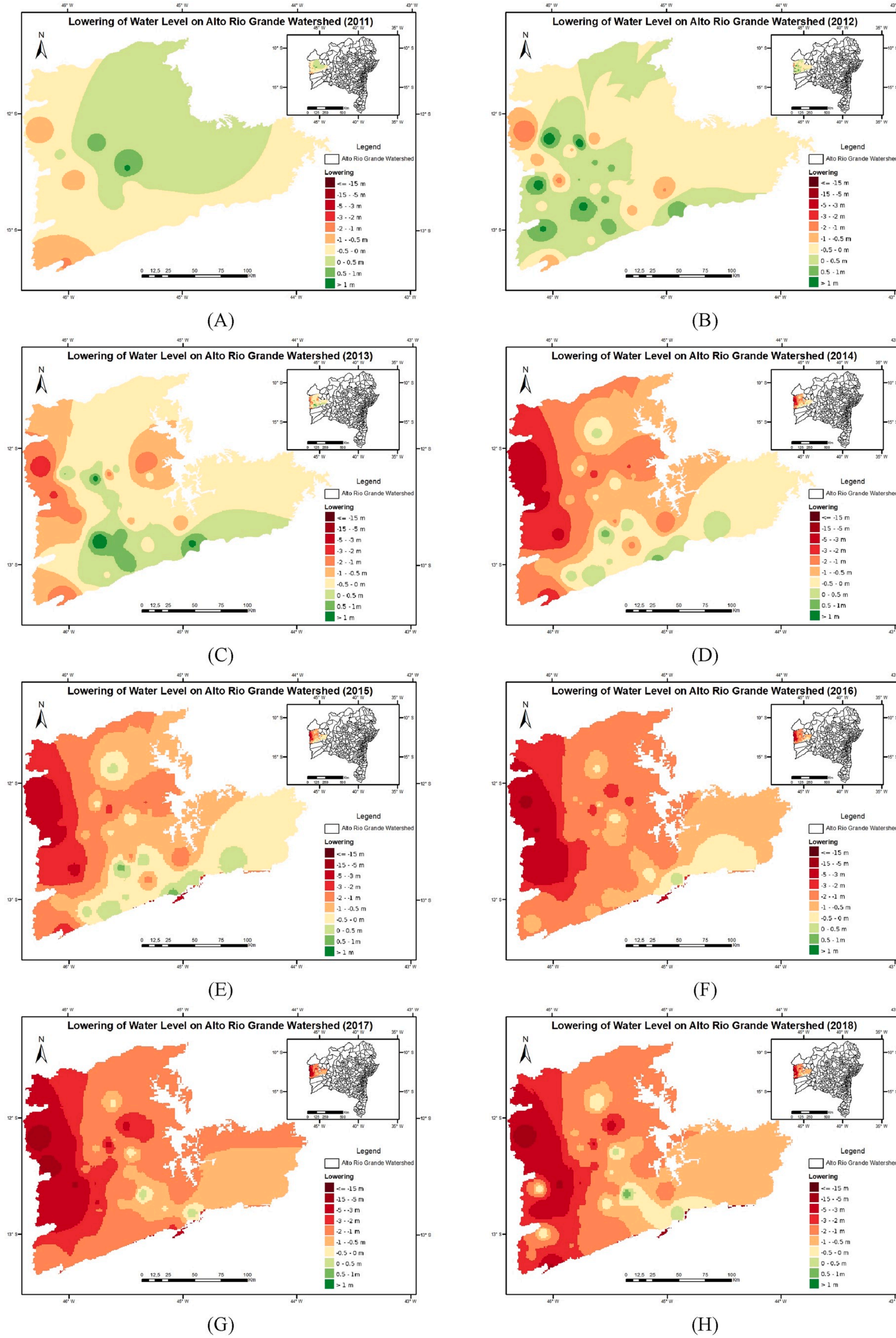


Fig. 9. (A to H) Maps of accumulated water level drawdown from 2011 to the end of 2018.

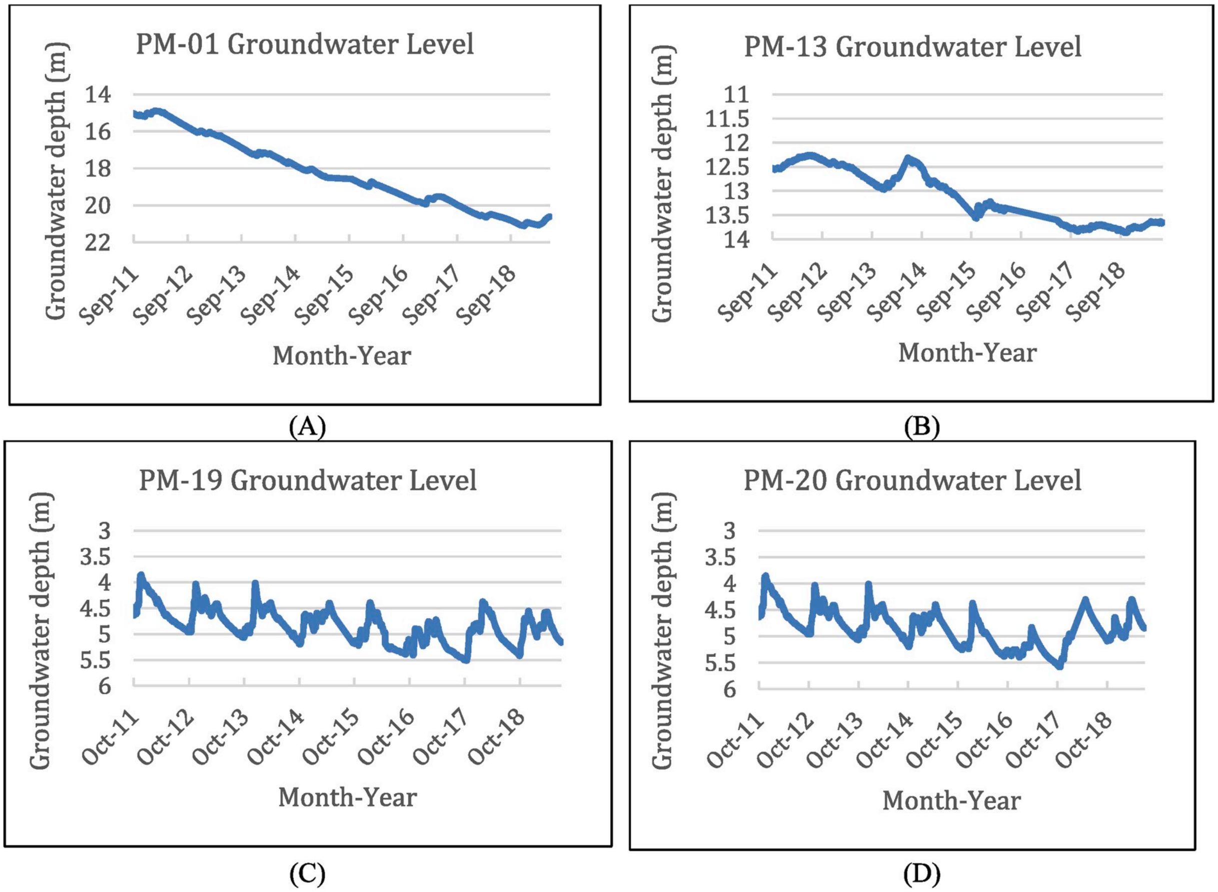


Fig. 10. Water level relatively smooth variation for PM01 and PM13 wells for the monitored period (A and B, respectively). Seasonally variable trend observed for PM19 and PM20 wells on the same period (C and D, respectively). Stabilization and even a slight recovery of groundwater head are noticeable by the end of the analyzed period.

4.3. River flow variation on Alto Grande watershed

Possible variations on surface water resources availability due to the increasing demand and % reduction on precipitation (RP), presented on previous sections, were analyzed by a comparative evaluation of Q_{lt} e Q_{90} (average and minimum average flow). Data from 1977 to 2010 and from 2011 to 2017 for the five gauging stations were analyzed (Fig. 5 and Table 1).

The results characterize a tendency of decrease of mean and minimum yields in all five stations considered. The percentage reduction on river flow rates between 1977 and 2010 and from 2011 to 2017 for Q_{lt} was, on average, 34% of the total flow, ranging from 23.9 to 46.4% for the fluviometric stations considered. For the minimum flow rate considered (Q_{90}), these ratios were similar, ranging from 24,1–53.5% between stations, corresponding to an average of 40,4%, as presented in Table 1. In others words, an average reduction of 34% and 40% was observed respectively, for long-term average and minimum flows considering the five gauging stations. This tendency is a short-term climate variation, but was useful for the comparison carried out here.

4.4. Groundwater head variation

The groundwater head monitoring data and ensuing analysis of RIMAS network database showed an interesting behavior regarding phreatic level variations over the monitored period. Fig. 9 brings the total head drawdown at the end of each year from 2011 to 2018 and a progressive increase of groundwater head drawdown of Urucuia Aquifer for the Alto Grande basin is observed throughout the period. For the majority of wells where monitoring data are available up to 2018, a progressively lower water table occurs. In addition, this head decline is much bigger in the western portion of the basin, with smaller effects towards the east. In the western portion of the aquifer, the groundwater level decrease towards the end of the 2011–2018 period reached up to 4.5 m. Only three wells presented a groundwater level drawdown bigger than 5.0 m: PM01 (6.63 m), PM04 (5.73 m) and PM 24 (5.88 m). The downstream portion of the basin eastwards showed a maximum head decline varying between 0.5 and 1.0 m or an increase of the same range, a situation quite different from the west. A considerable increase of the area affected by a bigger groundwater head drop is clear from the comparison of Fig. 9B with Fig. 9 H.

The shape of water level reduction at the end of 2015 (Fig. 9 E) is very similar to the reduction of precipitation in the previous period, presented on Fig. 7 B. However, a climate oscillation alone cannot fully explain the water level drawdown, as it is bigger than the rate of reduction in precipitation, thus indicating a possible over-exploitation of the aquifer in this watershed, as already suggested by Gonçalves et al. (2016).

Four monitoring wells were selected to present the two main groundwater hydrograph patterns in the region. The boreholes are open to the aquifer between 63 m (PM20) to 101 m (PM13), with PM 01 (83 m) and PM19 (91 m), showing intermediate depths. Fig. 10 shows the hydrographs of those wells, with a striking variation in behavior, depending on location and depth of the well. One pattern shows a clear influence of the seasonal rainfall regime, with a smooth descent trend in dry years and a smooth and recent recover after this period (Fig. 10C and D).

The second pattern, represented by the graph on Fig. 11A, shows a steady head decline with a very small recover during 2018, with no

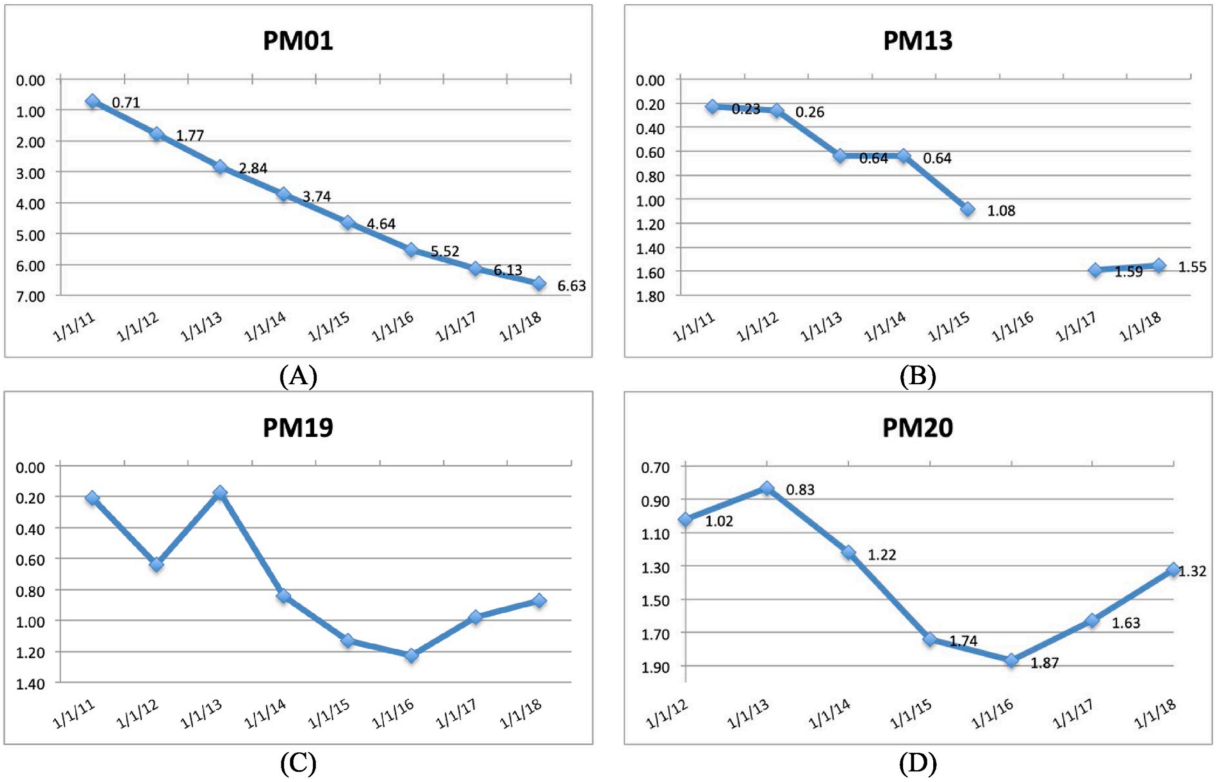


Fig. 11. Data from absolute accumulated decline in groundwater head from 2011 to the end of 2018 for wells PM19, PM20, PM01 e PM13.

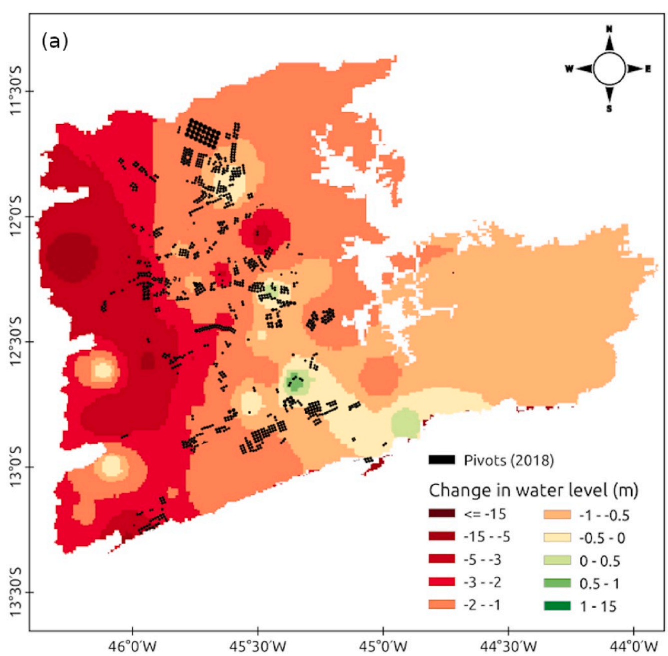


Fig. 12. Accumulated depletion of water level and central pivots installed up to 2018 in Grande river basin.

seasonal effects. The graph on Fig. 10B shows a mixed pattern, with an increase during 2013 and then a constant decrease up until September of 2017. Most of the other wells, though, show a steady decline between the beginning of the monitoring and the end of 2018.

Based on the monitoring data of the RIMAS network, new estimations exhibited the absolute groundwater level drop, on yearly basis, during the monitored period (2011–2018). Fig. 11 brings examples of this analysis for the same wells of Fig. 10. Groundwater head presents a constant downward trend towards the end of 2018 only for PM01 (Fig. 11A) with a constant lowering of groundwater head in the western part of the aquifer (even after the end of the last drought season on 2016), where the highest drawdown is present (6.63 m). On the Central portion of the aquifer some of these wells (PM19 and PM20) show a light recovery, while others, such as PM13, present a stabilization of the drawdown.

Fig. 12 shows the overlap of pivots installed in Rio Grande watershed (Fig. 8) and accumulated water level drawdown (Fig. 9H). The majority of pivots are installed on the center of the basin, in a region with accumulated drawdown varying between 0.5 and 2.0 m with some minor areas with up to 5.0 m drawdown in the western portion of the area.

Gonçalves et al. (2020), using GRACE data to quantify the depletion of water storage on UAS, observed a strong negative trend in the total water storage, at a rate of 6.5 ± 2.6 mm yr^{-1}. The authors related this reduction predominantly to an anthropogenic increase in evapotranspiration, due to poorly controlled groundwater abstraction and subsequent use in crop irrigation. However, this negative trend has a low statistical significance. Reduction in terrestrial water storage observed by Gonçalves et al. (2020) is reported as concentrated in the rainy season, and groundwater pumping is absent in this period. When comparing the period analyzed by those authors with a larger period, as presented on Fig. 6 and on Fig. 7, there is a significant (100–200 mm. yr^{-1}) reduction in precipitation.

The rainfall volume reduction (see Figs. 6 and 7), along with the increase in surface and groundwater exploitation in the headwaters of Alto Grande watershed, seems to have caused an expressive depletion of groundwater level from 2013 to 2016. Demand increase was mainly due to new central pivots installed in the period, especially in the central portion of the basin. The biggest water level drop is located in the western portion of UAS, which is also the region with the biggest reduction in precipitation. In this period, head drop on this western portion reached values up to 6.63 m. Figs. 10 and 11 shows that some recovery of water levels was observed after the end of the last drought, in 2016.

Establishing the relative quantitative contribution of the two driving effects (reduction on precipitation and increase in groundwater pumping) on the observed water level drawdown demands a longer monitoring period to provide a sharper estimation of groundwater flow regime in the affected zone, which is not currently available. Still, a hydrogeological numerical model with the MODFLOW code (Mcdonald and Harbaugh, 1988) is currently under development in the Grande basin. Preliminary results will enable a more precise estimation of the subsurface flow and the effect of the reducing rainfall intensity and increasing demand on the groundwater level variation in the region. Some other modeling experiences in the region have addressed this issue, as the work by Engelbrecht and Chang (2015), but further research is necessary. This approach has proved useful and has been applied in many other areas of the globe in the assessment of the impact of agriculture and climate change on groundwater resources (Han et al., 2018; Jeong et al., 2018; Hu et al., 2016; Gong et al., 2012; Singh et al., 2010; Florio et al., 2014).

Data already obtained has provided a basis to inferring that some of the western portion of Alto Grande watershed, near the headwaters, has a surface and groundwater over-exploitation process in course that should be better monitored to avoid water conflicts. It is necessary to implement an improved monitoring and management system to foster knowledge on the effects of possible climate change associated to the increasing demand over groundwater in the region, so that controlling and mitigating measures can be enforced, ensuring resource sustainability for the future.

5. Concluding remarks

Natural and man-induced variations in groundwater and surface water discharge and volumes influence the availability of this precious resource for irrigated agriculture and deserve a close look from scientists, stakeholders and the society in general. Prediction and quantification of the fluctuations is complex, and are related to climatic variables and anthropic actions. The evaluation of those conditionings in the present work focused on rainfall variations (resulting from climate oscillations) and the increase of water use for irrigation (demand growing at a fast pace), and consequent impacts on streamflow and groundwater levels. Setting a database of hydrological and groundwater monitoring results allowed a comparative analysis.

Geological settings of the study area compose a relatively simple conceptual framework, with a predominantly free aquifer, with locally deep water table, especially near the western border of the system. Eastwards aquifer depth reduces and water table gets nearer to the surface, with fluctuations more conspicuous than in the deeper water table area to the west.

Rainfall had a clear declining trend throughout the monitoring period, especially on western portions of Alto Grande watershed, representing a period of severe drought in the region, along with a persisting expansion of irrigated agriculture in the same period. These settings - reduction of rainfall volumes from 2013 to 2017 in the study area, with the increase in surface and groundwater exploitation - lead to a persistent, though not ubiquitous, groundwater level decline, sometimes higher than 5.0 m. These variations were caused by a significant reduction of precipitation values and an increase in water demand by the installation of central pivots throughout the watershed and were not homogenous. As the reduction of precipitation due to the climate oscillation alone does not fully explain the water level drawdown, a possible over-exploitation of the aquifer in this watershed can also be pointed as one of the causes of the observed water drown. Nevertheless, it was not possible to link unequivocally such causes and the observed effect. The relative contribution of these individual conditionings remains, therefore, to be adequately quantified for longer monitoring periods. Risks associated with an incipient hydric stress situation point to the need to implement a management system ensuring resource sustainability for the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Eduardo A.G. Marques: Funding acquisition, Project administration, Formal analysis, Conceptualization, Methodology, Investigation, Data curation, Supervision. **Gerson C. Silva Junior:** Project administration, Funding acquisition, Formal analysis, Conceptualization, Methodology, Supervision, Data curation, Investigation. **Glauco Z.S. Eger:** Formal analysis, Investigation. **Archange M. Ilambwetsi:** Formal analysis, Investigation. **Pousa Raphael:** Investigation, Formal analysis. **Tarcila N. Generoso:** Formal analysis, Investigation. **Josiane Oliveira:** Formal analysis, Investigation. **Jales N. Júnior:** Investigation, Formal analysis.

Acknowledgments

Authors would like to thank PRODEAGRO (Bahia State Agribusiness Development Program) for the financial support for this research.

References

Agência Nacional de Águas - ANA, 2013. Estudos hidrogeológicos na Bacia Hidrográfica do São Francisco—Sistema Aquífero Urucuia/Areado e Sistema Aquífero Bambuí. Comitê Bacia Hidrográfica do São Francisco accessed on. http://cbhsaofrancisco.org.br. (Accessed 12 February 2020).

Agência Nacional de Águas – ANA, 2017. Estudos hidrogeológicos e de vulnerabilidade do Sistema Aquífero Urucuia e proposição de modelo de gestão integrada compartilhada: resumo executivo. Agência Nacional de Águas. Elaboração e Execução: Consórcio Engecorps – Walm. Brasília: ANA 100 (In Portuguese).

Amorim Júnior, V., Lima, O.A.L., 2007. Avaliação hidrogeológica do Aquífero Urucuia na Bacia do Rio das Fêmeas (BA) usando resistividade e polarização induzida. Rev. Bras. Geofís. 25 (2), 117–129 (In Portuguese).

Araújo, R.S., Alves, M.G., Condesso de Melo, M.T., Chrispim, Z.M.P., Mendes, M.P., Silva Junior, G.C., 2015. Water resource management: a comparative evaluation of Brazil, Rio de Janeiro, the European Union, and Portugal. Sci. Total Environ. 511, 815–828.

Barbosa, N.S., Leal, R.B.L., Mello, J.C., Peixinho, M.A.L., Santos, C.B., Santos, R.L., Barbosa, N.S., 2017. Conceptual hydrogeologic model of central-western Urucuia aquifer system, Brazil. Águas Subterrâneas 31 (1), 1–19.

Bocanegra, E., Manzano, M., Custodio, E., Silva, Junior G.C., Betancur, T., 2016. Comparing management actions in groundwater related wetlands that provide significant services to human welfare in ibero-America. Episodes 39, 19–28.

Bonfim, L.F.C., Gomes, R.A.A.D., 2004. Aquífero Urucuia – Geometria e Espessura: Ideias para Discussão, vol. 13. Congresso Brasileiro de Águas Subterrâneas, Cuiabá (MT) (In Portuguese).

Campos, J.E.G., Dardenne, M.A., 1999. Distribuição, estratigrafia e sistemas deposicionais do Grupo Urucuia – cretáceo superior da bacia Sanfranciscana. Geociencias 18 (2), 481–499 (In Portuguese).

Chang, H.K., Silva, F.P., 2015. Contribuição ao arcabouço geológico do sistema aquífero Urucuia. São Paulo, UNESP, *Geociências* 34 (4), 872–882 (In Portuguese).

Cristo, V.N., Silva Junior, G.C., Eger, G.Z.S., Silveira, P.M., Menezes, J.M., 2015. Modelo Conceitual do Aquífero de Itaipuaçu em Maricá - RJ Com Uso de Ferramentas Hidrogeoquímicas e Hidrodinâmicas. Rev. Bras. Rec. Hídricos 20, 1063–1075 (In Portuguese).

Engelbrecht, B.Z., Chang, H.K., 2015. Simulação numérica do fluxo de águas do Sistema Aquífero Urucuia na bacia hidrogeológica do Rio Corrente (BA). Águas Subterrâneas 29 (2), 244–256 (In Portuguese).

Florio, E.L., Mercau, J.L., Jobbágy, E.G., Nosetto, M.D., 2014. Interactive effects of water-table depth, rainfall variation, and sowing date on maize production in the Western Pampas. Agric. Water Manag. 146 (1), 75–83. https://doi.org/10.1016/j.agwat.2014.07.022.

Frisbee, M.D., Phillips, F.M., Campbell, A.R., Liu, F., Sanchez, S.A., 2011. Streamflow generation in a large, alpine watershed in the southern Rocky Mountains of Colorado: is streamflow generation simply the aggregation of hillslope runoff responses? Water Resour. Res. 47 (6) https://doi.org/10.1029/2010WR009391, 2011, 1-18 W06512.

Gaspar, M.T.P., Campos, J.E.G.O., 2007. Sistema aquífero Urucuia. Rev. Bras. Geociencias 37 (Supl. 4), 216–226 (In Portuguese).

Gaspar, M.T.P., Campos, J.E.G., Moraes, R.A.V., 2012. Determinação das espessuras do Sistema Aquífero Urucuia a partir de estudo geofísico. Rev. Bras. Geociencias 42 (Supl. 1), 154–166 (In Portuguese).

Gonçalves, R.D., Engelbrecht, B.Z., Chang, H.K., 2016. Análise hidrológica de séries históricas da Bacia do Rio Grande (BA): contribuição do Sistema Aquífero Urucuia. Águas Subterrâneas 30 (2), 190. https://doi.org/10.14295/ras.v30i2.28514.

Gonçalves, R.D., Stollberg, R., Weiss, H., Chang, H.K., 2020. Using GRACE to quantify the depletion of terrestrial water storage in Northeastern Brazil: the Urucuia Aquifer System. Sci. Total Environ. 705, 135845. https://doi.org/10.1016/j.scitotenv.2019.135845.

Gong, J., Wang, K., Kellomäki, S., Zhang, C., Martikainen, P.J., Shurpali, N., 2012. Modeling water table changes in boreal peatlands of Finland under changing climate conditions. Ecol. Model. 244, 65–78.

Han, W.S., Graham, J.P., Choung, S., Park, E., Choi, W., Kim, Y.S., 2018. Local-scale variability in groundwater resources: cedar creek watershed, Wisconsin. U.S.A. *J. Hydro-Environ. Res*. 20 (1), 38–51. https://doi.org/10.1016/j.jher.2018.04.007.

Hu, X., Shi, L., Zeng, J., Yang, J., Zha, Y., Yao, Y., Cao, G., 2016. Estimation of actual irrigation amount and its impact on groundwater depletion: a case study in the Hebei Plain, China. J. Hydrol. 543 (1), 433–449. https://doi.org/10.1016/j.jhydrol.2016.10.020.

Jeong, J., Park, E., Han, W.S., Kim, K.Y., Suk, H., Jo, S.B., 2018. A generalized groundwater fluctuation model based on precipitation for estimating water table levels of deep unconfined aquifers. J. Hydrol. 562 (1), 749–757. https://doi.org/10.1016/j.jhydrol.2018.05.055.

Kim, I., Park, D., Kyung, D., Kim, G., Kim, S., Lee, J., 2016. Comparative influences of precipitation and river stage on groundwater levels in near-river areas. Sustainability 8 (1), 1–16.

Kong, F., Song, J., Zhang, Yan, Guobin, F., Cheng, D., Zhang, G., Xue, Y., 2019. Surface water groundwater interaction in the guanzhong section of the weihe river basin, China. Groundwater 57 (4), 647–660. https://doi.org/10.1111/gwat.12854.

Manzione, R.L., Soldera, B.C., Wendland, E.C., 2016. Groundwater system response at sites with different agricultural land uses: case of the Guarani Aquifer outcrop area, Brotas/SP-Brazil. Hydrol. Sci. J. 61. http://02626667.2016.1154148.

Mcdonald, M.G., Harbaugh, B.R., 1988. MODFLOW: a modular three-dimensional finite-difference ground-water flow model. Techniques of Groundwater of Water-Resources Investigations of the United States Geological Survey, Book 6. US Government Printing Office, Washington. Chapter A1.

Pimentel, A.L., Aquino, R.F., Silva, R.C.A., Vieira, C.M.B., 2000. Estimativa da recarga do aquífero Urucuia na sub-bacia do rio das Fêmeas – oeste da Bahia, utilizando separação de hidrogramas. In: ABGE, Cong. Aproveitamentos e Gestão de Recursos Hídricos em países de Idioma Português, vol. 1. Atas (In Portuguese).

Pousa, R., Costa, M.H., Pimenta, F.M., Fontes, V.C., de Brito, V.F.A., Castro, M., 2019. Climate change and intense irrigation growth in western Bahia, Brazil: the urgent need for hydroclimatic monitoring. Water 11 (1), 933 1–93321. https://doi.org/10.3390/w11050933.

Pruski, F.F., Nunes, A. de A., Pruski, P.L., Rodriguez, R., del, G., 2013. Improved regionalization of streamflow by use of the streamflow equivalent of precipitation as an explanatory variable. J. Hydrol. 476, 52–71.

Rodríguez, N.B., McGuire, K.J., Klaus, J., 2018. Time-varying storage—water age relationships in a catchment with a Mediterranean climate. Water Resour. Res. 54 (1), 3988–4008. https://doi.org/10.1029/2017WR021964.

Seabra, V.S., Silva Junior, G.C., Cruz, C.B.M., 2009. The use of geoprocessing to assess vulnerability on the east coast aquifers of Rio de Janeiro State. Brazil. *Env. Geol.* 57 (3), 665–674.

Shaw, G.D., Conklin, M.H., Nimz, G.J., Liu, F., 2014. Groundwater and surface water flow to the merced river, yosemite valley, California: ^{36}Cl and Cl^{-} evidence *water resour*. Res. 50 (3), 1943–1959. https://doi.org/10.1002/2013WR014222.

Singh, A., Krause, P., Panda, S.N., Flugel, W.A., 2010. Rising water table: a threat to sustainable agriculture in an irrigated semi-arid region of Haryana, India, *Agric*. Water Manag. 97 (10), 1443–1451. https://doi.org/10.1016/j.agwat.2010.04.

Sousa, J.R.C., 2017. Hydrology Plus: sistema computacional para estudos meteorológicos e hidrológicos. Tese (Doutorado Engenharia Agrícola) - Universidade Federal de Viçosa, Viçosa, MG, 2017 (In Portuguese).

Vrzel, J., Solomon, D.K., Blažeka, Ž., Ogrinc, N., 2018. The study of the interactions between groundwater and Sava River water in Ljubljansko polje aquifer (Slovenia). J. Hydrol. 556 (1), 384–396. https://doi.org/10.1016/j.jhydrol.2017.11.022.

Wendland, E.C., Barreto, C.E.A.G., Gomes, L.H., 2007. Water balance in the Guarani aquifer outcrop zone based on hydrogeologic monitoring. J. of Hydrol. 342 (3-4). http://10.1016/j.jhydrol.2007.05.033.

Xavier, Alexandre C., King, Carey W. e Scanlon, Bridget, R., 2016. Daily gridded meteorological variables in Brazil (1980-2013). Int. J. Climatol. 36 (6), 2644–2659.